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Passivity control via Power Shaping of a wind turbine in a dispersed network

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ABSTRACT

The connection of renewable energy conversion systems in distribution networks must comply with codes for assuring power quality as well as the grid assistance demands. The new operating requirements cannot always be achieved from the control strategies that have been employed for years in conventional distribution systems. In this context, this paper addresses the problem of controlling a wind turbine from passivity control concepts. In particular a control strategy based on a new approach to the passivity theory, known as Power Shaping, is proposed. This approach allows to consider pervasive dissipation. The proposed strategy is evaluated in the context of extreme operating conditions showing capability to ride through grid failures. In this way, the simulation results encourage the application of concepts of Power Shaping in more complex systems of distributed generation.

1. Introduction

The renewable energy conversions systems constitute an advantageous alternative to increase the local supply of electricity in existing distribution grids, which generally are weak.

The Control of active power of these systems is essential to the proper distribution of electric energy. Active power control is used to balance demand and supply, so contributing to frequency stability, whereas reactive power control is commonly used in voltage regulation. Wind energy penetration into the electric markets was almost negligible during past decades. Therefore, wind turbines have been predominantly operated to maximize the wind energy capture. However, as wind energy penetration raises, the new technical regulations for grid connection of wind energy conversion systems (WECS) tend to give priority to wind power quality over power quantity. Moreover, wind power turbines are increasingly required to share some of the duties carried out today by the conventional power plants, such as active and reactive power regulation even ride through grid failures. In this sense specifications for high power turbines have been recently introduced [19,20,23].

The conventional control techniques are not always solve the requirements of the real codes, for this reason in last years new control strategies based on advanced control ideas have

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been explored [20]. Among the more promising control theories to deal with the new challenges of renewable dispersed generation are those based on passivity ideas.

Passive systems constitute an important class of dynamic systems, for which the stored energy cannot exceed the energy supplied to it from the outside, with the different being the dissipated energy. The first controller based on concepts of passivity was introduced over two decades ago. Since then the theory of passivity has constantly evolved leading to robust control strategies which have been applied to electric machines, energy systems, magnetic levitation system, power converters, etc [6,5,14–16].

The Power Shaping as all techniques derived from passivity, is characterized by not requiring the linearization of the model neither to establish a Lyapunov function that guarantees the stability of the controlled system nor to obtain the domain of attraction of it. In contrast to passive control based on damping assigning, the Power Shaping Control does not presents obstacles of pervasive dissipation at equilibrium [1,3,4].

In this context, and considering one of the structures of more versatile systems of conversion of wind energy (turbine of horizontal axis, gear box, three-phase rotor wound induction machine (DFIG) and a back to back converter), we propose an active power control strategy to take advantage of the energetic utilization [11,6] which is based on concepts of passive systems, particularly on Power Shaping ideas. The proposed control is evaluated in a test platform system that has been used for testing different control strategies [13,17,22,21].

The structure of this paper is the following. Section 2 introduce the basics to synthesize a controller using the technique Power Shaping Control. Section 3 presents the dynamical model of the DFIG employed in the control law development. The control law is obtained in Section 4 and afterward evaluated in Section 5. Finally the conclusions are summarized.

2. Fundamentals for Power Shaping Control

Given a dynamical system:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases}, \tag{1}$$

where $f(x):\mathbb{R}^n \to \mathbb{R}^n$, $g(x):\mathbb{R}^n \to \mathbb{R}^n \times \mathbb{R}^m$, n is the number of states and m is the number of inputs of the system. The following propositions are used to obtain a stabilizing control by power shaping [1,3]. Assume:

1. There exist a matrix $Q:\mathbb{R}^n \to \mathbb{R}^{n\times n}$, full range, non singular that solves the differential equation:

$$\nabla(Q(x)f(x)) = [\nabla(Q(x)f(x))]^T, \tag{2}$$

and furthermore verifies that:

$$Q(x) + Q(x)^T \leq 0. \tag{3}$$

2. There is a scalar function $P_a:\mathbb{R}^n \to \mathbb{R}$, positive definite in the neighborhood of an equilibrium point x^*, which verifies the following partial differential equation:

$$g^{\perp}(x)Q^{-1}(x)\nabla P_a(x) = 0, \tag{4}$$

where $g^{\perp}(x)$ is the left annihilator of $g(x)$. That is to say:

$$g^{\perp}(x)g(x) = 0. \tag{5}$$

3. The point of equilibrium x^* is asymptotically stable, with Lyapunov function $P_d(x)$ such that:

$$\nabla P_d(x^*) = 0, \tag{6}$$

$$\nabla^2 P_d(x^*) > 0. \tag{7}$$

Where the total power function of the system is given by:

$$P_d(x) = P(x) + P_a(x), \tag{8}$$

and

$$P(x) = \int [Q(x)f(x)]^T dx. \tag{9}$$

Under these conditions the control law is:

$$u = \left[g^T Q^T Q g\right]^{-1} g^T Q^T \nabla P_a. \tag{10}$$

3. Dynamical model of wind turbine

The system considered in this section is shown in Fig. 1 where can appreciate a wound rotor asynchronous generator connected to the grid. This generator is impulsed by a three-bladed horizontal-shaft wind turbine. The wind turbine are coupled by a gear box.

The operation of a machine of induction is analyzed using the theory of rotating fields and the well known d-q model [8]. The voltages in the generator stator and rotor are:

$$\overrightarrow{u_{sg}} = R_s \overrightarrow{i_{sg}} + \frac{d\lambda_{sg}}{dt}, \tag{11}$$

$$\overrightarrow{u_{rg}} = R_r \overrightarrow{i_{rg}} + \frac{d\lambda_{rg}}{dt}, \tag{12}$$

where R_s and R_r are the stator and rotor winding resistances, respectively, λ_{sg} and λ_{rg} are the stator and rotor fluxes in a

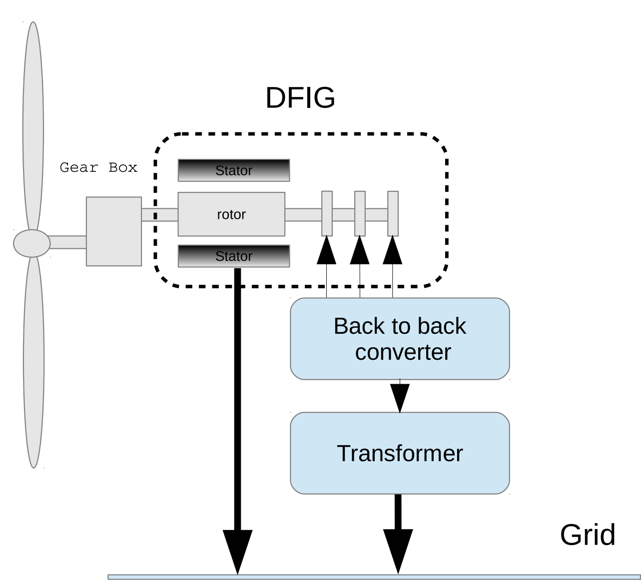

Fig. 1 – Wind turbine configuration.

generic reference frame, i_{sg} and i_{rg} are the stator and rotor currents.

The expressions for the derivative of the rotor current components in the generic framework (x, y) can be obtained from equations (11) and (12):

$$\frac{di_{rx}}{dt} = -\frac{R_r}{L_r}i_{rx} + \frac{1}{L_r}u_{rx}, \tag{13}$$

$$\frac{di_{ry}}{dt} = -\frac{R_r}{L_r}i_{ry} + \frac{1}{L_r}u_{ry}. \tag{14}$$

Then the electromagnetic torque:

$$T_e = \frac{3}{2}np(\lambda_{sx}i_{sy} - \lambda_{sy}i_{sx}), \tag{15}$$

where np is the number of pair of poles of the asynchronous generator, λ_{sx} and λ_{sy} are the fluxes linkage on the (x,y) framework. The expressions for active and reactive power are given by:

$$P = \frac{3}{2}(u_x i_x + u_y i_y) = \frac{3}{2}(U i_y), \tag{16}$$

$$Q = \frac{3}{2}(u_y i_x - u_x i_y) = \frac{3}{2}(U i_x), \tag{17}$$

where can see that, considering vector control on a particular framework such that $u_x = 0$ and $u_y = U$, the active and reactive powers can be controlled independently [10,18].

On the other hand, the angular acceleration is given by:

$$\frac{d\omega}{dt} = \frac{np}{J}(T_e - B_r\omega - T_m), \tag{18}$$

where B_r is the combined coefficient of load friction, ω the angular speed of the rotor, T_m the mechanic torque and J is the inertia of the system.

The torque and the mechanic power of a wind turbine are defined by Ref. [11]:

$$T_m = \frac{\pi\rho r^2}{2}v^3 C_p(\lambda)/\Omega_t, \tag{19}$$

$$P_t = \frac{\pi\rho r^2}{2}v^3 C_p(\lambda), \tag{20}$$

where ρ is the density of the air, r the radius of the wind turbine, v is wind speed, $C_p(\lambda)$ the coefficient of power, $\lambda = \frac{\Omega_t r}{v}$ the ratio of the blade tip speed, Ω_t is the rotational speed of the wind turbine.

From equations (13), (14) and (18), expression (1) is:

$$\dot{x} = \begin{pmatrix} -\frac{R_r}{L_r}x_3 \\ -\frac{R_r}{L_r}x_4 \\ 2\left(-\frac{B_r x_5}{J} - \frac{3Ux_4L_m}{J\omega L_s}\right) \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{L_r} \\ 0 \end{pmatrix}u, \tag{21}$$

where x_3, x_4 and x_5 are the rotor current components in the d–q axes and the speed rotor respectively. In equation (21), the feed-forward actions have been considered to eliminate the coupling between $\dot{i}_{rx}$ and $\dot{i}_{ry}$. These actions cancel the voltages u_{rx} and u_{ry} in the equations (14) and (13).

4. Control law

As mentioned above, to employ the Power Shaping technique is necessary to propose a matrix $Q(x)$ that verifies the equations (2) and (3).

The matrix $Q(x)$ proposed in this work can be found in Appendix A. To control the active power of the DFIG, $g(x)$ can be taken as shown in the expression (21).

Then, the left annihilator:

$$g^{\perp}(x) = (0 \quad 0 \quad 1), \tag{22}$$

which checks the expression (5) is proposed.

Thus, the expression (4) for the system becomes:

$$g^{\perp}(x)Q^{-1}(x)\nabla P_a(x) = (g_1 \quad g_2 \quad g_3)\nabla P_a = 0. \tag{23}$$

For clarity the details of the calculation of $P_a(x)$ has been summarized in Appendix B.

Finally the control law for the DFIG generator considered results:

$$u = b_1\left(-6b_2^2\frac{\partial P_a}{\partial x_4} + 3b_2\frac{\partial P_a}{\partial x_5}\right), \tag{24}$$

where:

$$b_1 = \frac{(JR_r\omega L_s)^4}{36(UL_m)^4L_r^2 + 9(JR_rU\omega L_mL_s)^2}, \tag{25}$$

$$b_2 = \frac{UL_m}{JR_r\omega L_s}, \tag{26}$$

being L_m the magnetizing inductance, L_r the rotor self-inductance and L_s the stator self-inductance.

5. Simulation results

In this section, the Power Shaping controller is evaluated in grid connection. In Fig. 2 is shown a wind turbine of 1.5 MW connected to a system of electric distribution of 25 kV. The system exports power to a network of 120 kV through a line of 30 km. This systems has been used as a testing platform for different control strategies [22,21].

The blade pitch control actuates when the available wind power is greater than the nominal value. When the available wind energy is less than the nominal, the pitch angle of the blade is fixed to maximize the mechanical power delivered to the shaft [17].

The wind turbine reference speed for wind speeds below the rated is given by Ref. [13]:

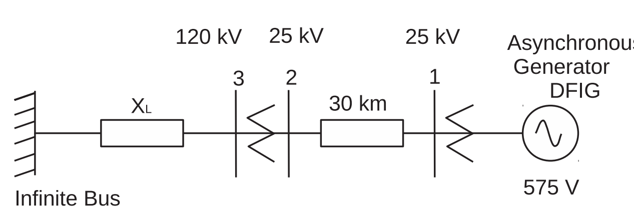

Fig. 2 – System analyzed.

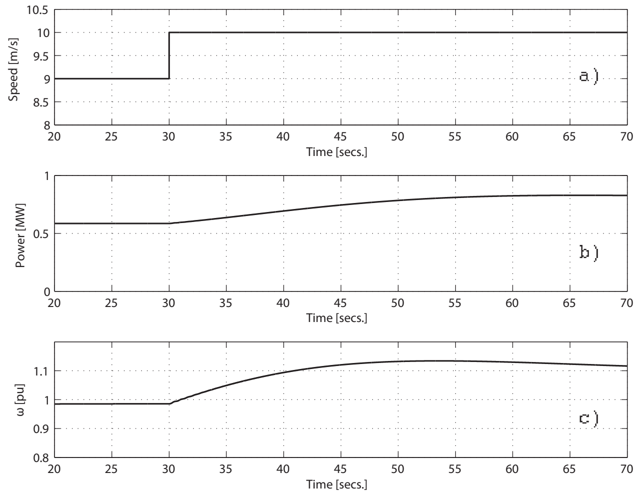

Fig. 3 – System behavior. a) Step of wind. b) Active power. c) Speed shaft.

$$\omega_{ref} = -0.67P_e^2 + 1.42P_e + 0.51, \tag{27}$$

being, P_e wind power extracted. The reactive power is controlled by regulating the voltage at the connection point of the wind generator.

Three cases are analyzed for the purpose of demonstrating the feasibility of the control.

Even though real wind does not occur as a series of steps, this kind of change is used because it is a standard testing signal that permits a clear interpretation of the system behavior. In this way, Fig. 3a shows a step change in the wind velocity which implies changing the turbine aerodynamic torque producing an acceleration torque (T_t-T_g) which, in turns, increases the turbine speed (Fig. 3c). As a consequence of the turbine speed increment, the proposed control forces the extracted power to follow the reference one defined in expression (27) increasing the delivered power (Fig. 3b). Then, the proposed control assures that the transitory behavior of the wind turbine evolves towards the maximum efficiency operating point at 10 m/s.

Fig. 4 shows the system behavior in presence of a voltage sag of 10% during 2 s. Meanwhile, in Fig. 4a the voltage sag indicated corresponds to the infinite bus in Fig. 2(full line), the dashed line presented the voltage at the DFIG machine. The voltage at the connection point is recovered via the reactive (proportional) power control. This control, which is not studied in this work, by virtue of vector control operates decoupled from the active power control. Part (c) of Fig. 4 shows that, despite the magnitude of the perturbation in the infinite bus, the proposed control (active power) allows that the turbine speed remains almost unchanged. Indeed, at the same time that voltage suddenly decreases so does the electromagnetic torque and the extracted power, due to wind velocity remains unchanged an accelerating torque appears (T_t-T_g). As a consequence, the proposed control forces the machine to deliver into the grid an active power which counteracts the increment in the kinetic energy due to (T_t-T_g). This explains the peak of active power injected into the grid just after the fault Fig. 4c.

Fig. 5 shows the performance of the system against an extreme fault in the infinite bus, a voltage dip of 60% and 0.6 s. The nowadays connection codes require that wind turbines have the ability to ride through grid failures, otherwise the failure can be strengthened harming the rest of the electrical system. Fig. 5a shows voltages in the main bus (solid line) and at the terminals of the generator (dashed line), respectively. As in the previous case, in part (b) of Fig. 5 a strong injection of active power to the grid prevents a turbine speed increase. This fact can be verified in part (c) of the figure where, despite the severity of the fault, there are no significant changes in the speed of the turbine that could force disconnection. At time 12 s, once the fault is removed, the controller brings to the steady state the electrical power delivered by the DFIG.

The simulation results show that despite the severe conditions the system presents a good performance. These first

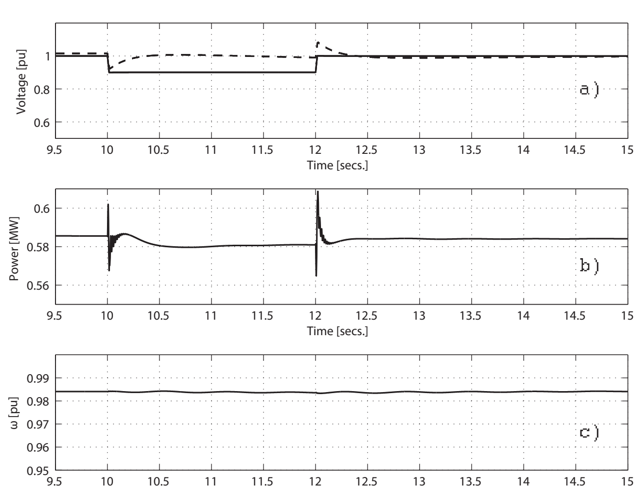

Fig. 4 – Voltage step. a) Voltage step in the infinite bus (solid line) and the voltage variation in the connection point (dash line). b) Active power. c) Speed shaft.

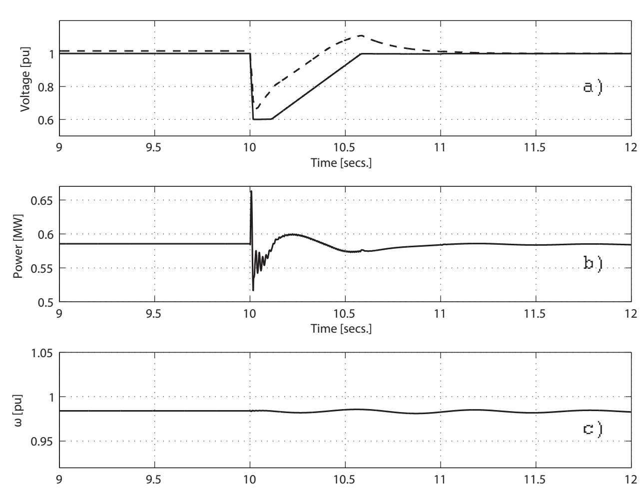

Fig. 5 – Sag voltage a) Sag voltage in the infinite bus. b) Active power. c) Speed shaft.

results are promising and quite optimistic with the use of the method in more complex systems.

6. Conclusions

This article analyzes the use of Power Shaping concepts, a new approach of passive control theory, to synthesize a controller for the active power of a wind turbine with wound rotor asynchronous generator connected to a weak network. Simulations results allow to verify the feasibility of the proposed control design in presence of different network failures and variations in the wind resource. These first results are promising and encourage to extend the field of application of the Power Shaping design to the reactive power control in order to assist the network against failures in more complex renewable distributed generation systems, whose characteristics make difficult or impossible the application of other conventional control technique.

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Appendix A. Calculation of Q (x)

To reduce the number of equations involved in expression (2), the following values for the elements of Q(x) are adopted:

$$q_{12} = 0, q_{13} = 0, q_{21} = 0, q_{31} = 0, \tag{A.1}$$

$$q_{23} = \frac{J}{B_r}\left(\frac{q_{32}R_r}{L_r} + \frac{3q_{33}UL_m}{J\omega L_s}\right). \tag{A.2}$$

To ensure that $Q(x) + Q(x)^T$ is a negative semi-definite matrix, the principal minors are checked [9].

Taken $q_{11} = -1$, the second principal minor is:

$$A_2 = 4q_{11}q_{22} \geq 0, \tag{A.3}$$

The third ones becomes:

$$A_3 = 8q_{22}q_{33} + \frac{18(q_{33}UL_mL_r)^2}{(JR_r\omega L_s)^2} \leq 0. \tag{A.4}$$

To ensures the expression (A.4):

$$q_{22} = -\frac{18(UL_mL_r)^2}{k(JR_r\omega L_s)^2}, \tag{A.5}$$

is taken, where the constant k should be allocated to meet the inequality 3, in this way $k = 3$ is chosen. For simplicity the value of q_{33} is assigned at -1. More details for the choice of Q(x) can be found in Ref. [2].

Appendix B. Calculation of P_a (x)

Values g_1, g_2 and g_3 for the developed system are:

$$g_1 = 0, g2 = \frac{3UL_mL_r}{Jq_{22}R_r\omega L_s}, g_3 = \frac{1}{q_{33}}. \tag{B.1}$$

The solution of the partial differential equation is given by:

$$P_a(x) = \Psi\left(-\frac{g_3}{g_2}x_4 + x_5\right), \tag{B.2}$$

where $\Psi : \mathbb{R}^2 \to \mathbb{R}$ must be chosen such that $P_d(x) = P(x) + P_a$ has a minimum in x^*. To solve the corresponding partial differential equation the procedure described in Ref. [12] can be used.

The result of first term of the expression (8) becomes:

$$P(x) = \frac{T_m x_5}{J} + \frac{B_r x_5^2}{2J} + \frac{R_r x_3^2}{2L_r} - \frac{q_{22}R_r x_4^2}{2L_r}. \tag{B.3}$$

Given the conditions for $P_d(x)$, posed in the equations (6) and (7), we can build a function that has the form of the equation (B.2). In this way is proposed:

$$P_a(x) = -\frac{R_r x_3^{*2}}{2L_r} + k_a(z - z^*)^2 + k_b(z - z^*), \tag{B.4}$$

where k_a and k_b are scalars, and z and z^* are given by:

$$z = \left(-\frac{g_3}{g_2}x_4 + x_5\right), \tag{B.5}$$

$$z^* = \left(-\frac{g_3}{g_2}x_4^* + x_5^*\right). \tag{B.6}$$

From equations (6) and (21) the value of k_a, k_b and g_2 can be obtained, resulting in:

$$k_a = 1, \tag{B.7}$$

$$k_b = q_{33}\frac{T_e^*}{J}, \tag{B.8}$$

$$g_2 = \frac{T_e^*}{x_4^*}\frac{L_r}{R_r J}. \tag{B.9}$$

The hessian $\nabla^2 P_d$ is given by:

$$\nabla^2 P_d = \left\langle \begin{pmatrix} R_r/L_r & 0 & 0 \\ 0 & t_1 & t_3 \\ 0 & t_3 & t_2 \end{pmatrix} \right\rangle 0, \tag{B.10}$$

$$t_1 = 2\left(\frac{g_3}{g_2}\right)^2 k_a + \frac{6(UL_m)^2 L_r}{R_r(J\omega L_s)^2}, \tag{B.11}$$

$$t_2 = \frac{B_r}{J} + 2k_a, t_3 = -2k_a\frac{g_3}{g_2}. \tag{B.12}$$

The expression (B.10) is positive definite. Thus we can conclude that it verifies the existence of a minimum in x^*.

REFERENCES

[1] García-Canseco Eloísa, Jeltsema Dimitri, Ortega Romeo, Scherpen Jacquelien MA. Power-based control of physical systems. Automatica January 2010;46(1). ISSN: 0005-1098:127–32.

[2] Favache A, Dochain D, Winkin JJ. Power-shaping control: writing the system dynamics into the Brayton - Moser form. Systems Control Lett August 2011;60(8). ISSN: 0167-6911:618–24.
[3] Garcia-Canseco E, Ortega R, Scherpen JMA, Jeltsema. Power shaping control of nonlinear systems: a Benchmark Example. Lecture Notes in Control and Snformation Sciences 2007;366. ISSN: 01708643:135–46. LNCIS.
[4] Ortega R, Jeltsema D, Scherpen JMA. Power shaping: a new paradigm for stabilization of nonlinear RLC circuits. Automatic Control, IEEE Transactions 2003;48(10). ISSN: 0018-9286:1762–7.
[5] Fernández RD, Battaiotto PE, Mantz RJ. Wind farm control based on passivity. In: Industrial Technology (ICIT), 2010 IEEE International Conference on 2010. pp. 1000–5.
[6] Fernández RD, Mantz RJ, Battaiotto PE. Wind farm control for stabilisation of electrical networks based on passivity. Int J Control 2010;83(1). ISSN: 00207179:105–14.
[8] Wu Bin, Lang Yongqiang, Zargari Navid, Kouro Samir. Power conversion and control of wind energy systems. Willey; 2011.
[9] Strang G. Linear algebra and its applications. Thompson Learning; 2006.
[10] Vas P. Sensorless vector and direct torque control. Oxford Science Publications; 1998.
[11] Bianchi Fernando Daniel, De Battista Hernán, Mantz Ricardo Julian. Wind turbine control systems: principles, modelling and gain scheduling designIn Advances in industrial control series. London: Springer-Verlag London Ltd.; 2006.
[12] Myint-U T. Linear partial differential equations for scientist and engineers. Boston: Birkhäuser; 2007.
[13] Miller NW, Sanchez-Gasca Juan J, Price WW, Delmerico RW. Dynamic modeling of GE 1.5 and 3.6 MW wind turbine-generators for stability simulations. In: Power engineering society general meeting. IEEE, vol. 3; 2003. pp. 1977–83.
[14] Liu Juhua, Krogh BH, Ydstie BE. Passivity-based robust control for power systems subject to wind power variability. In: American Control Conference (ACC). ISSN0743-1619 2011. pp. 4149–54.
[15] Petrovic V, Ortega R, Stankovic AM. A globally convergent energy-based controller for PM synchronous motors, decision and control 1999. In: Proceedings of the 38th IEEE Conference. ISSN0191-2216, vol. 1; 1999. pp. 334–40.
[16] Rodriguez H. and Ortega R. and Escobar G. A robustly stable output feedback saturated controller for the Boost DC-to-DC converter, Decision and Control, 1999. Proceedings of the 38th IEEE Conference on, 2100-2105; 3, ISSN 0191–2216.
[17] Piwko R, Miller N, Sanchez-Gasca J, Yuan X, Renchang Dai and Lyons J. Integrating large wind farms into weak power grids with long transmission lines. In: Power electronics and motion control conference 2006. pp. 1–7. IPEMC 2006. CES/IEEE 5th International.
[18] Petersson A, Lennart Harnefors, Thiringer T. Comparison between stator-flux and grid-flux-oriented rotor current control of doubly-fed induction generators. In: Power electronics specialists conferencePESC 04. 2004 IEEE 35th Annual. ISSN0275-9306, vol. 1; 2004. pp. 482–6.
[19] Mantz Ricardo Julián, Battista Hernán De. Hydrogen production from idle generation capacity of wind turbines. Int J Hydrogen Energy August 2008;33(16). ISSN: 0360-3199:4291–300.
[20] Fernandez RD, Battaiotto PE, Mantz RJ. Impact of wind farms voltage regulation on the stability of the network frequency. Int J Hydrogen Energy July 2008;33(13). ISSN: 0360-3199:3543–8.
[21] Fernández RD, Mantz RJ, Battaiotto PE. Linear and non-linear control of wind farms. Contribution to the grid stability. Int J Hydrogen Energy June 2010;35(11). ISSN: 0360-3199:6019–24.
[22] Evangelista CA, Valenciaga F, Puleston P. Multivariable 2-sliding mode control for a wind energy system based on a double fed induction generator. Int J Hydrogen Energy July 2012;37(13). ISSN: 0360-3199:10070–5.
[23] Piwko R, Miller N, Girad R, MacDowell J, Clark K, Murdoch A. Generator fault tolerance and grid codes, Power and Energy Magazine, IEEE; 8(2), 18–26, ISSN 1540-7977.